

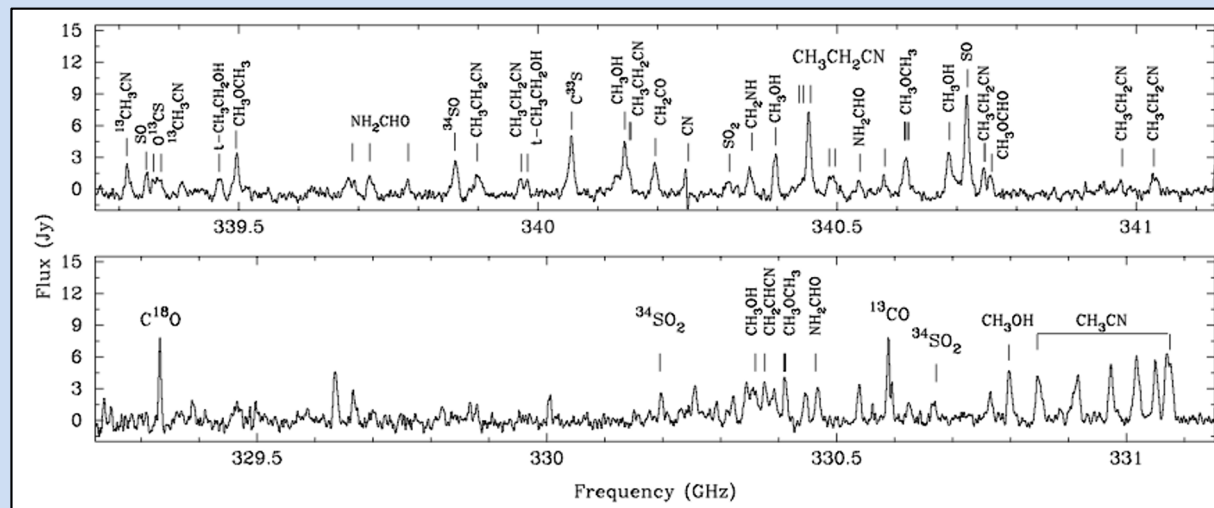


Spectral Line Interferometry

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Based on previous ERIS and NRAO lectures
and book *Synthesis Imaging in Radio Astronomy II*



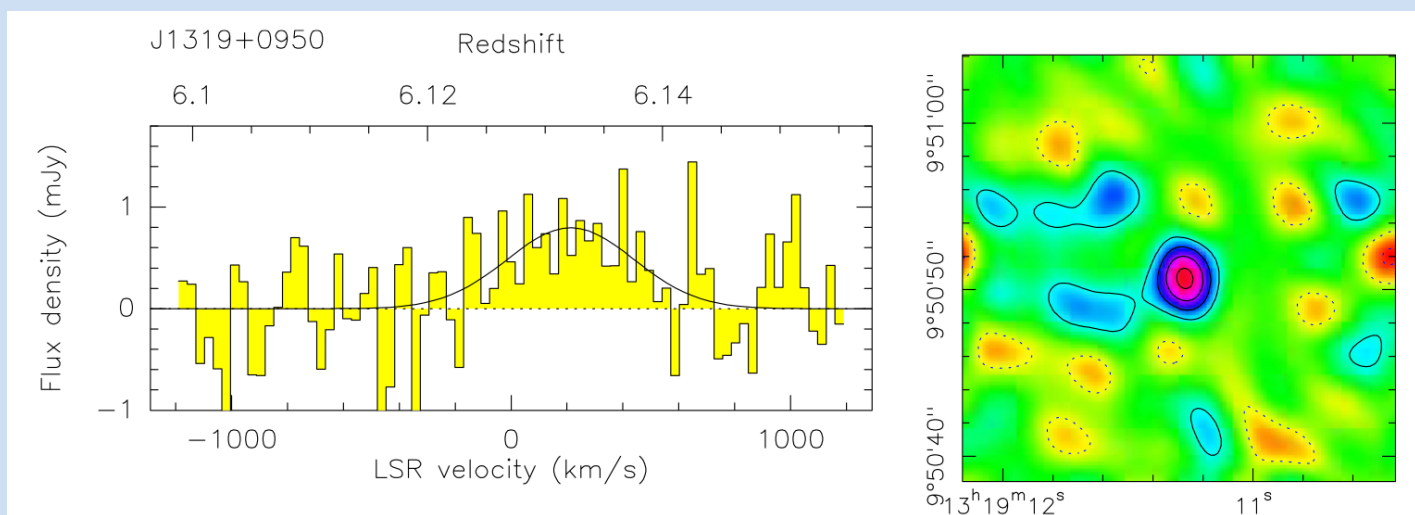
SMA spectrum showing molecular lines in a "hot core" (Rathborne et al. 2008)

What is spectral line interferometry?

Spectral line interferometry...

is observing many adjacent frequency channels with an interferometer for an object whose flux changes rapidly with frequency (analogous to spectroscopy in optical)

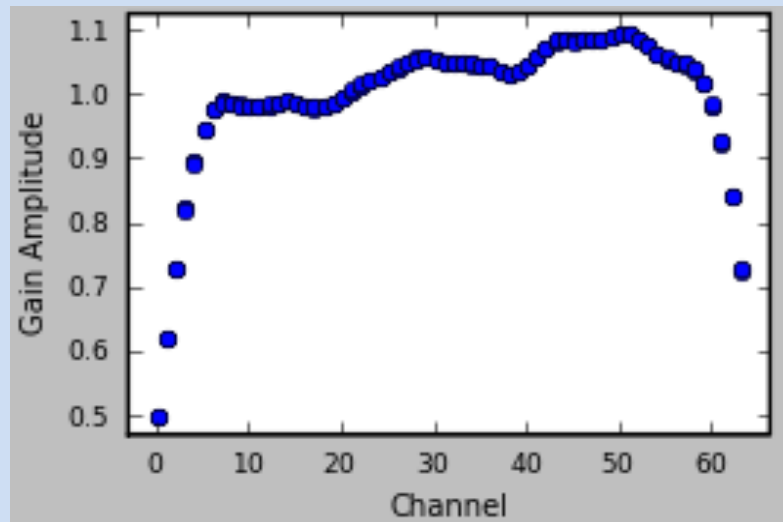
In essence, it gives you a third axis: frequency or velocity



CO(6-5) emission from a high redshift quasar observed with the Plateau de Bure Interferometer (Wang et al. 2011)

What is spectral line interferometry?

Today, even continuum observations are carried out with many channels (called pseudo-continuum)



Plot of response across a band for one VLA antenna as a function of channel, during reduction of **continuum data**

Therefore, you need to understand spectral line interferometry to do (almost all) interferometry!

Outline

Part I: Setting up your observation

Part II: Data reduction

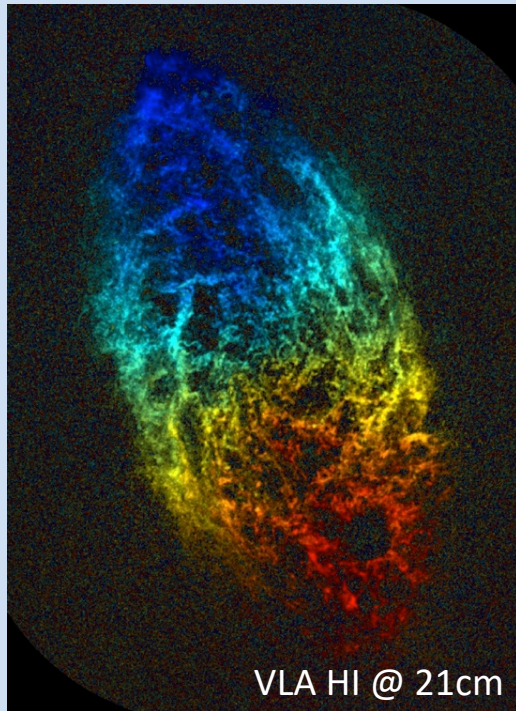
Part III: Image and spectral analysis

Part I: Setting up your observation

1. Choose your science case and line(s)
2. Choose your source(s) and research its properties
3. Choose your interferometer and configuration
4. Check source velocity reference frame, on-line Doppler tracking
5. Choose the channel width, total bandwidth and number of channels
6. Determine your required channel sensitivity and time on source
7. Choose your calibrators

1. Choose your science case and line(s)

Doppler shifts → Velocity fields



Velocity field of galaxy M33 in HI line. Colors show Doppler shift of line and brightness is proportional to HI column density (NRAO, Thilker et al.)

1. Choose spectral line(s) from science case
2. Find which telescopes have bands that contain these lines

Physical Properties from lines for science case

Dynamics

Optical depth

Excitation Temperature

Column density

Density

Turbulent motions

Magnetic field strength

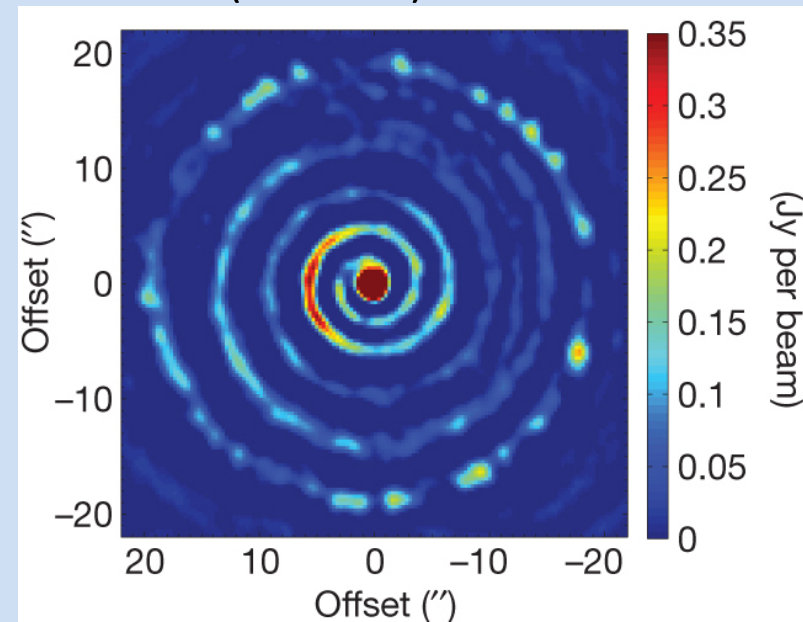
Chemistry

2. Choose your source(s) and research its/their properties

Learn about the object you wish to study, e.g.

- Position (and equinox)
- Size
- Velocity (and equinox/coordinate frame)
- Angular resolution required
- Estimated brightness (at required angular resolution)
- Previous spectra of the source
--> linewidths

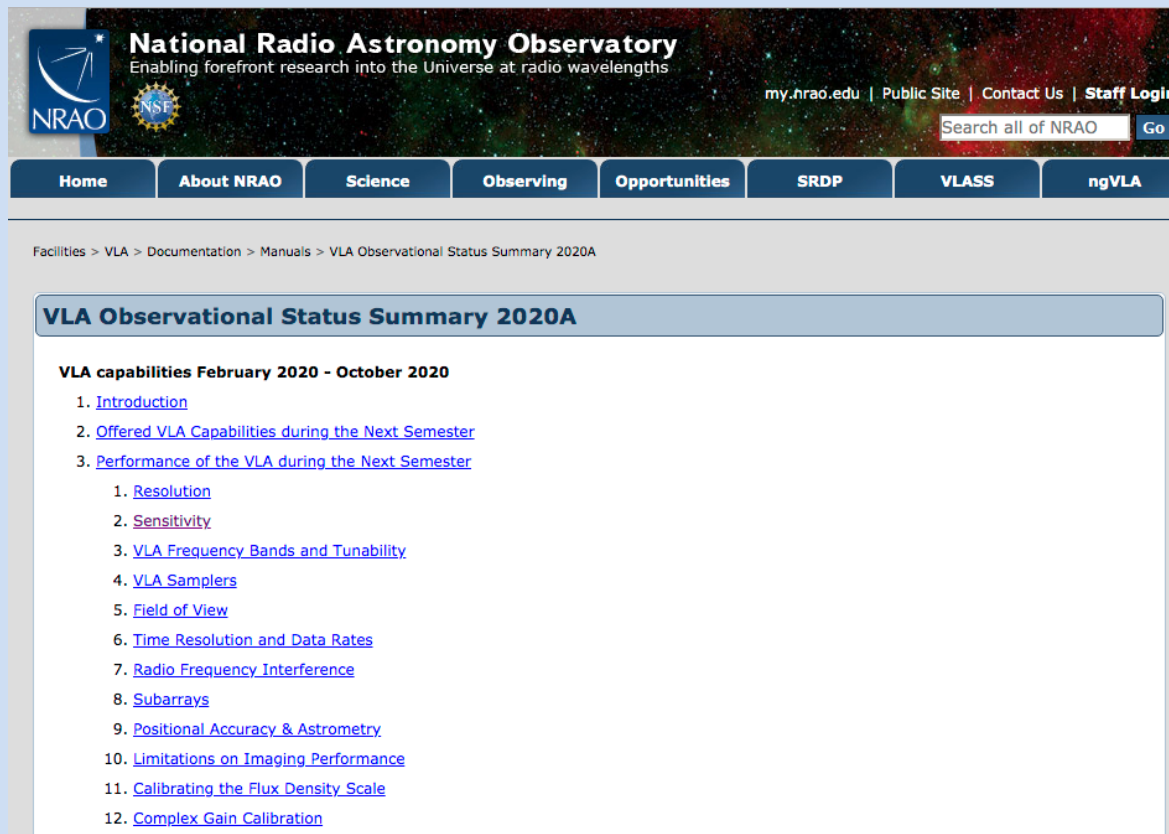
AGB star R Sculptoris
CO($J = 3 - 2$) with ALMA



Maercker et al. (2012)

3. Choose your interferometer and configuration

Read about telescopes online
(e.g. VLA Observational Status summary)

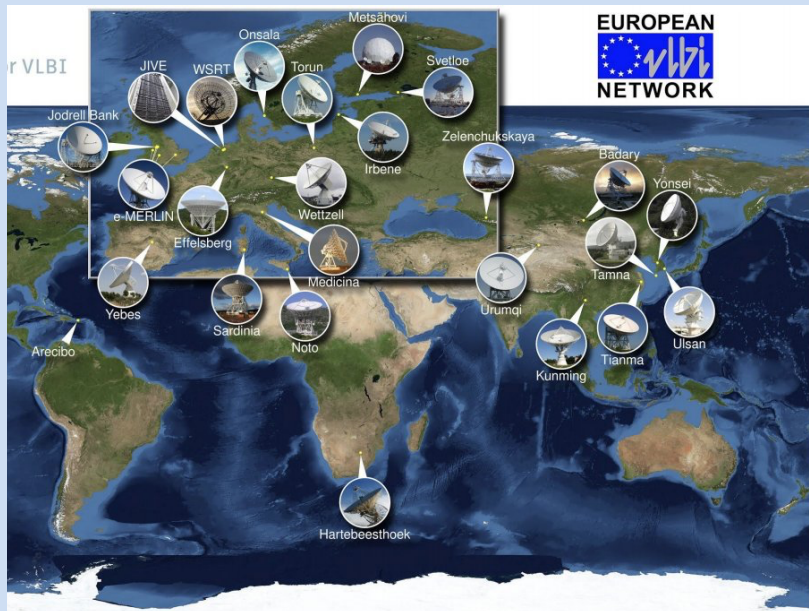


The screenshot shows the National Radio Astronomy Observatory (NRAO) website. The header includes the NRAO logo, the text "National Radio Astronomy Observatory" and "Enabling forefront research into the Universe at radio wavelengths", and navigation links for "my.nrao.edu", "Public Site", "Contact Us", and "Staff Login". A search bar is also present. Below the header is a navigation menu with buttons for "Home", "About NRAO", "Science", "Observing", "Opportunities", "SRDP", "VLASS", and "ngVLA". The main content area shows a breadcrumb trail: "Facilities > VLA > Documentation > Manuals > VLA Observational Status Summary 2020A". The page title is "VLA Observational Status Summary 2020A". The main content is titled "VLA capabilities February 2020 - October 2020" and lists 12 items:

- [1. Introduction](#)
- [2. Offered VLA Capabilities during the Next Semester](#)
- [3. Performance of the VLA during the Next Semester](#)
 - [1. Resolution](#)
 - [2. Sensitivity](#)
 - [3. VLA Frequency Bands and Tunability](#)
 - [4. VLA Samplers](#)
 - [5. Field of View](#)
 - [6. Time Resolution and Data Rates](#)
 - [7. Radio Frequency Interference](#)
 - [8. Subarrays](#)
 - [9. Positional Accuracy & Astrometry](#)
 - [10. Limitations on Imaging Performance](#)
 - [11. Calibrating the Flux Density Scale](#)
 - [12. Complex Gain Calibration](#)

3. Choose your interferometer and configuration

EVN



Larger arrays: better resolution! Good for bright, compact sources

Part of the ALMA Compact Array



Smaller arrays: have better surface brightness sensitivity so easier to detect extended or faint emission

4. Check source velocity reference frame

Need to always specify velocity reference frame:

Rest Frame	Corrected for	Amplitude of Correction (km/s)
Topocentric	Nothing	0
Geocentric	Earth rotation	0.5
Earth-Moon Barycentric	Effect of Moon on Earth	0.013
Heliocentric	Earth's orbital motion	30
Solar System Barycentric	Effect of planets on Sun	0.012
Local Standard of Rest (LSRK/D)	Solar motion	20
Galactocentric	Milky Way Rotation	230
Local Group Barycentric	Milky Way Motion	~100
Virgocentric	Local Group Motion	~300
Microwave background	Local Supercluster motion	~600

4. Check source velocity reference frame

- Optical Barycentric or Heliocentric system often used for extragalactic observations
- Radio Local Standard of Rest (LSR) used for Milky Way observations

Doppler shift and Doppler Tracking

Full relativistic equation:

$$\frac{\nu}{c} = \frac{\nu_0^2 - \nu^2}{\nu_0^2 + \nu^2}$$

Radio definition:

$$\frac{\nu_{\text{radio}}}{c} = \frac{\nu_0 - \nu}{\nu_0}$$

Optical definition:

$$\frac{\nu_{\text{optical}}}{c} = \frac{\lambda - \lambda_0}{\lambda_0}$$

Only good approximations for small bandwidths!

Doppler shift and Doppler Tracking

- **On-line Doppler tracking** automatically corrects to a given reference frame during the observation **in real time**
- The tracked or observed frequency is usually called the **sky frequency**
- However, for wide frequency bands (VLA, ALMA, SMA...) on-line Doppler tracking is not done/recommended as correction is **only strictly correct at one frequency**
- Instead “Doppler Setting” is used, i.e. sky frequency calculated once at the start of the observation
- Further corrections can be made during data reduction and imaging
- **Warning:** don't put lines too close to the edge of the band!

5. Choose the channel width, total bandwidth and number of channels

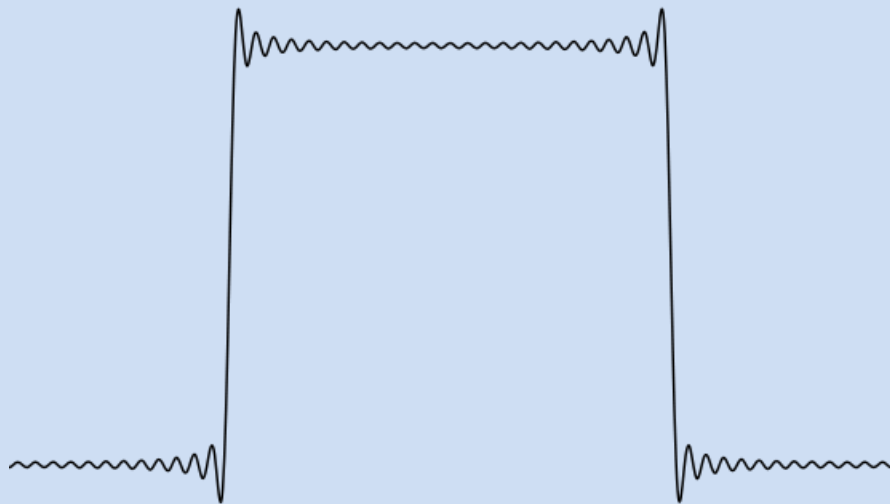
- Determine how many channels needed to adequately resolve your line (e.g. >5)
- Channel width determined by **required spectral resolution** and **required sensitivity at that resolution**:

$$\sigma_S = \frac{2kT_{\text{sys}}}{A_{\text{eff}}[N(N-1)\Delta\nu_{\text{RF}}\tau]^{1/2}}$$

- Total bandwidth should:
 - Leave good line-free channels at ends of band for continuum subtraction (end channels often bad)
- In a “lag” correlator, total number of channels is conserved, so total bandwidth is directly related to channel width

Gibbs Ringing and Hanning Smoothing

Gibbs Ringing



- See at channel edges
- Also see for bright lines e.g. masers, RFI

Fixed by

Hanning Smoothing

Smooth data with a running mean in frequency with weights:

0.5 for central channel
0.25 for adjacent channels

(i.e. triangular smoothing kernel)

Pro: reduces ringing

Con: reduces spectral resolution by factor of 2

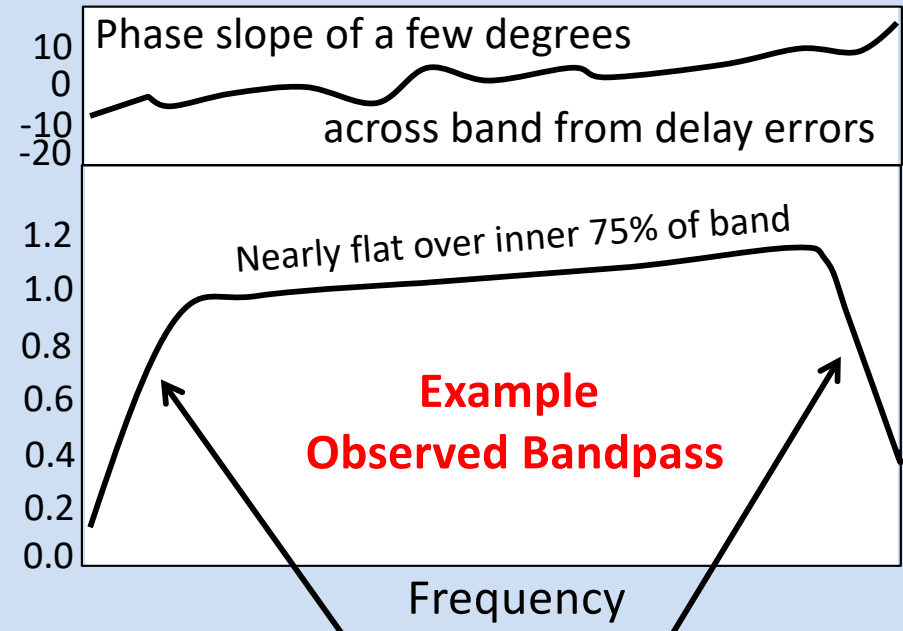
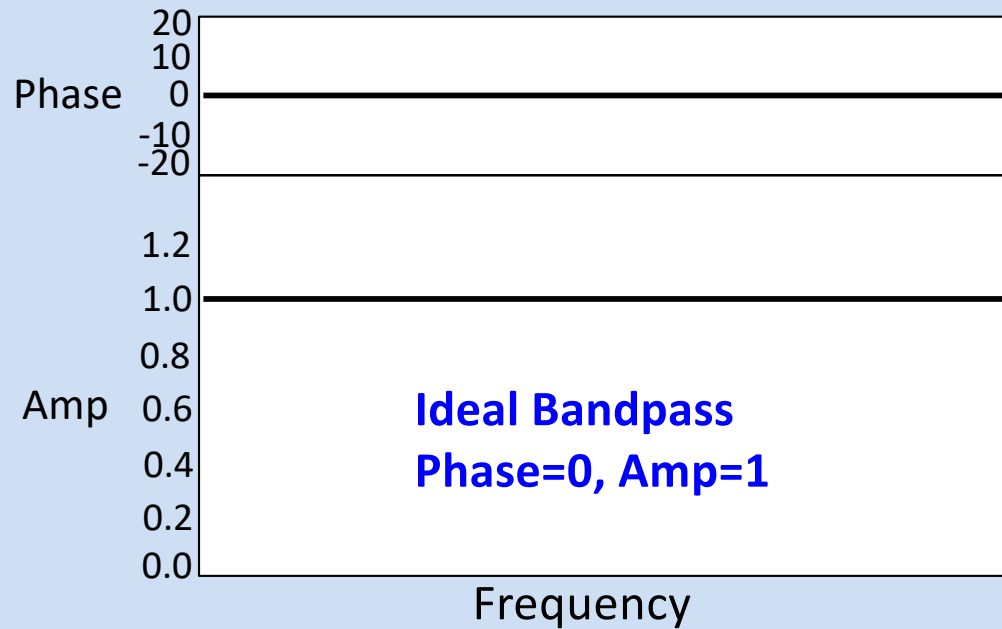
6. Determine your required channel sensitivity and time on source

- If **detection important**, need to detect line in **peak channel** with $>3-5$ sigma
- If **need to resolve emission in different channels** for e.g. dynamics, need to detect line in **faintest of these channels** with $>3-5$ sigma
- You should determine the estimated flux of the source (May need to convert from brightness temperature T_b or expected column density)
- Use sensitivity calculator to determine required time on-source (e.g. VLA, ALMA, EVN)

7. Choose your calibrators

Bandpass calibration

The bandpass is the spectral frequency response of an antenna to a spectrally flat source of unit amplitude



- Observed bandpass shape due primarily to electronics/ transmission systems of each antenna
- Different for each antenna

Edge roll-off caused by shape of bandpass filters

Bandpass calibration attempts to correct for the deviations of the observed bandpass from the ideal one

What makes a good bandpass calibrator?

Select a bright continuum source with:

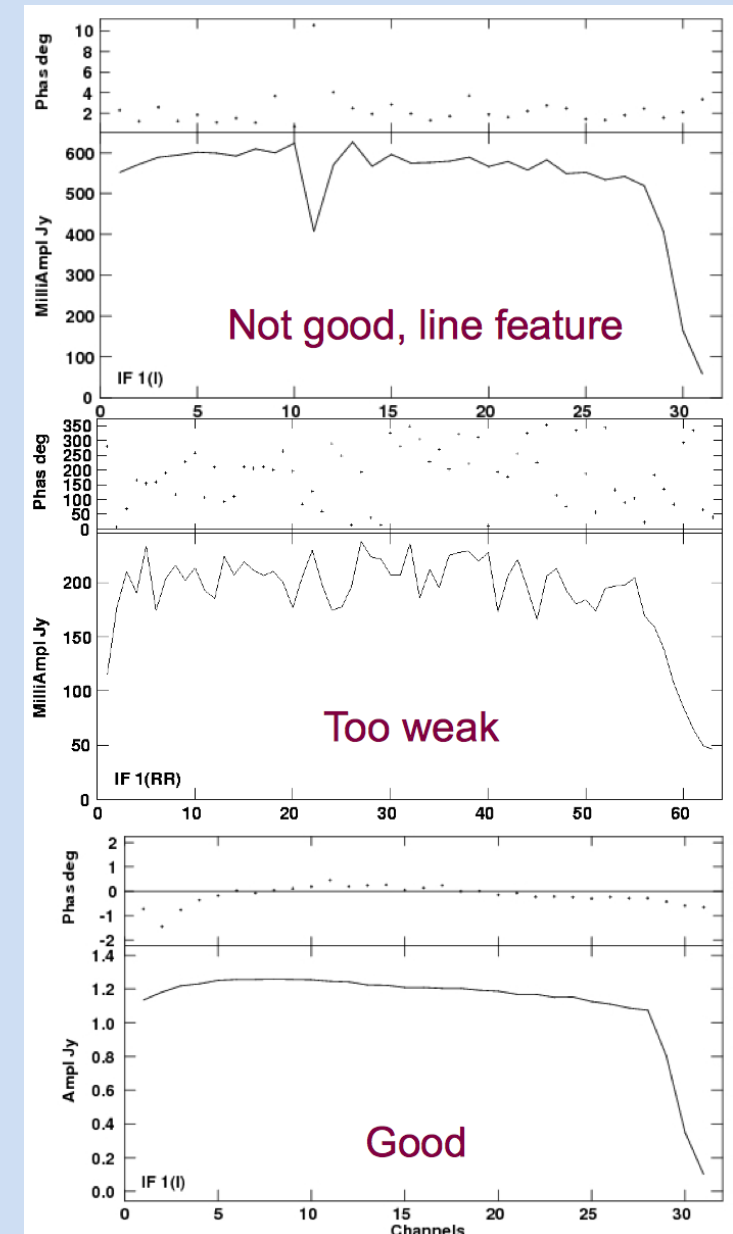
- High SNR in each channel
- Intrinsically flat spectrum
- No spectral lines/features
- No changes in structure across band (e.g. point source at all frequencies)

Calibration should not contribute to noise in target spectrum, i.e. in one channel:

bandpass SNR \gg target SNR

Can smooth the bandpass or fit polynomial to increase the SNR.

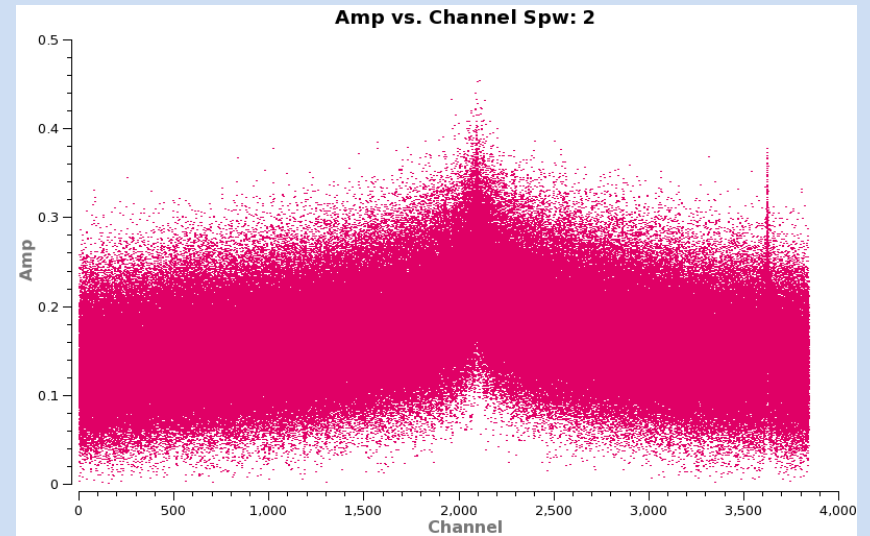
May need higher SNR for bandpass calibrator if looking for faint lines on strong continuum



7. Choose your calibrators

Flux calibration

- Check that there is an accurate model of the flux calibrator at these frequencies.
- In mm/sub-mm observing, if using a solar system object with an atmosphere for calibration (e.g. Jovian or Saturnian moons), be aware that these objects often have emission and/or absorption lines.
- In mm/sub-mm observing, lines are currently included in the models for Titan, Mars and Neptune and will be updated as more observations are performed.



Titan's spectrum in one spectral window in an observation

Part II: Data reduction

- Flagging methods
- Bandpass calibration
- Doppler correction
- Continuum subtraction
- Imaging of cubes

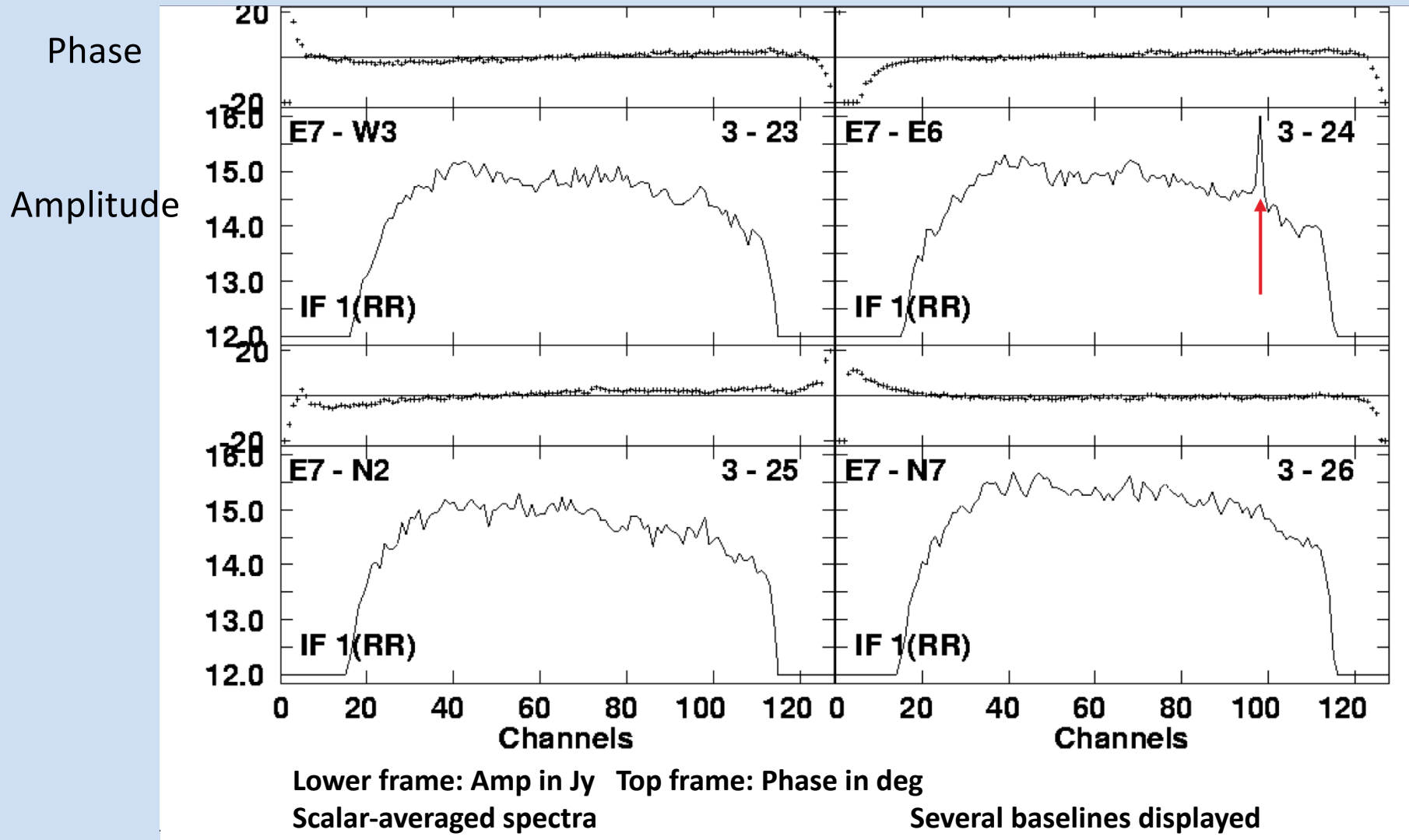
Flagging Methods – in frequency

- For large data sets, checking the data channel-by-channel is not practical
- This task can be simplified using approaches such as:
 - Examination of the scalar-averaged (in time) visibility spectra: check for dips or spikes
 - Use of automated flagging routines: these can flag data based on deviation from expected spectral behavior (e.g. AOFlagger)

But... if you are planning to make image cubes then try to avoid excessive frequency-dependent flagging which changes the uv-coverage and synthesized beam across the band

Flagging Methods – in frequency

Scalar-averaged visibility spectra can be helpful for spotting narrowband RFI



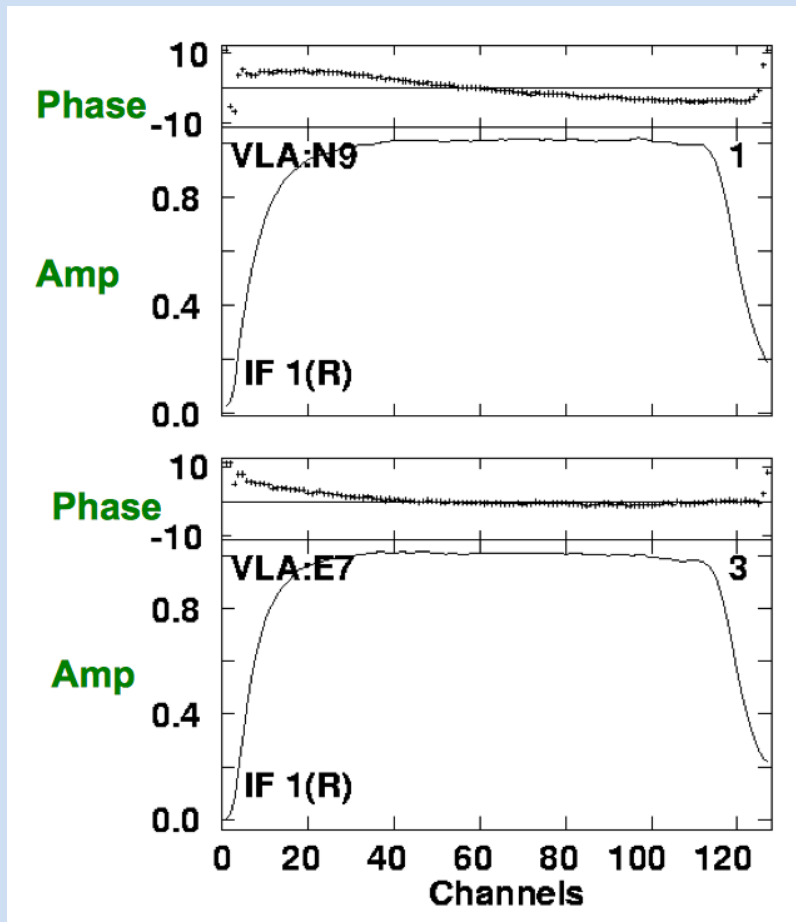
Flagging Methods – in time

- Can find bad data in time using the vector-averaged central ~75% of channels of the calibrator sources
- Can find problems affecting all frequency channels e.g. malfunctioning electronics or mechanical problems with a particular antenna
- Resulting flags can then (if needed) be copied to the other sources and applied to all spectral channels

Bandpass calibration

Has your bandpass calibration gone well?

Bandpass solutions



Examples of good-quality bandpass solutions for 2 antennas:

- Solutions should look comparable for all antennas
- Mean amplitude ~ 1 across useable portion of the band
- No sharp variations in amplitude and phase
- Variations are not dominated by noise

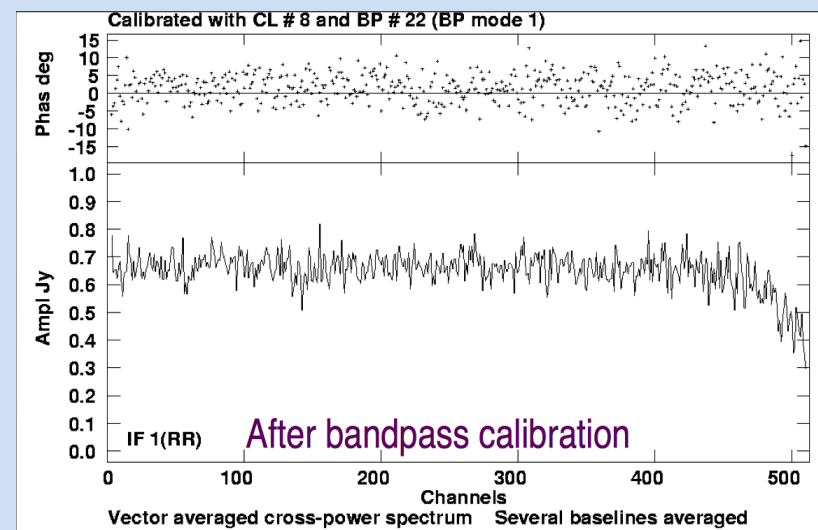
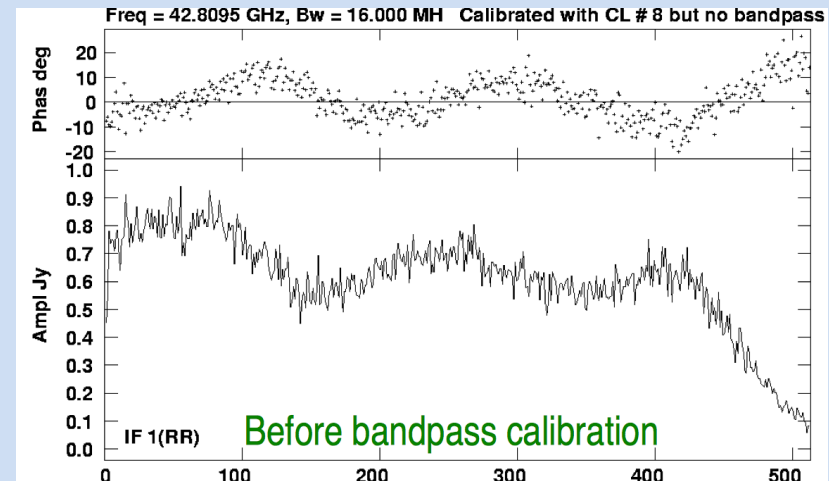
Bandpass calibration

Has your bandpass calibration gone well?

Another good way to check: examine spectra of a continuum (flat spectrum) source with BP corrections applied.

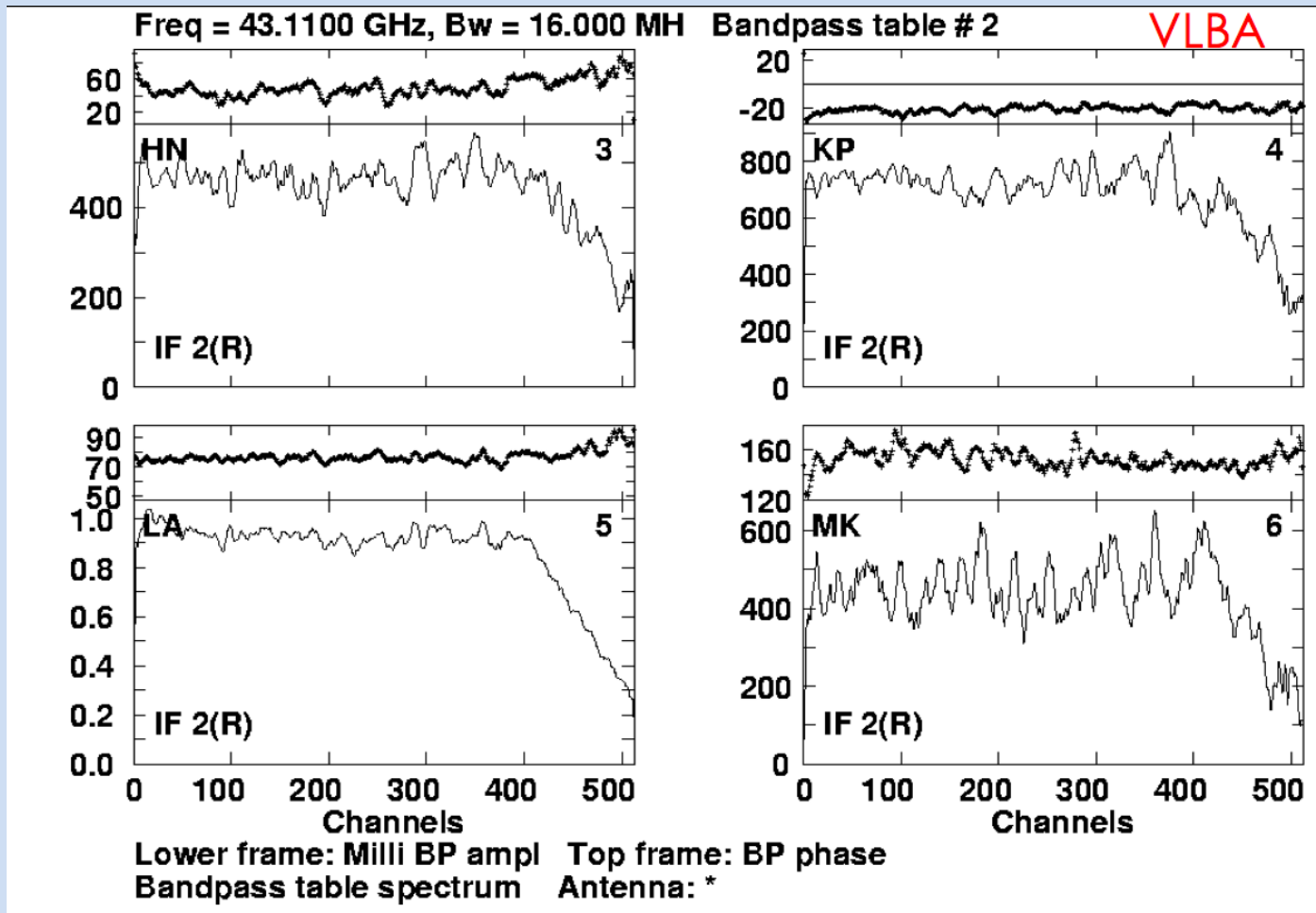
Checklist:

- ✓ Phases are flat across the band
- ✓ Amplitude is constant across the band
- ✓ Corrected data do not have significantly increased noise
- ✓ Absolute flux level is not biased high or low



Bandpass calibration

When has your bandpass calibration **not** gone well?



Plot of bandpass solutions for four antennas VLBA

Problems:

Amplitude has different normalisation for different antennas

Noise levels are high, and are different for different antennas

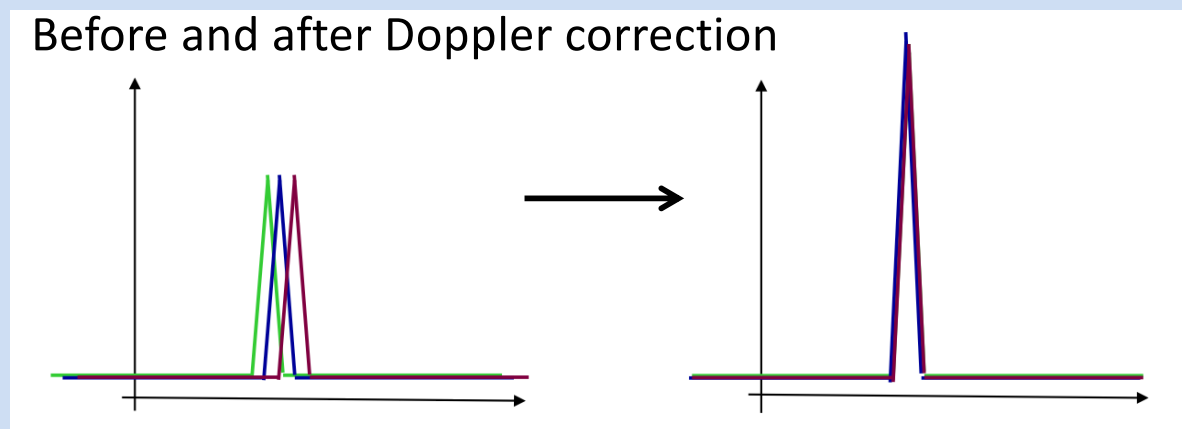
Possible causes:

- Poor pre-calibration
- Bad data

Doppler correction

- Often now done using **Doppler Setting** and further finer corrections during post-processing and imaging (see slides from Part I).
- Within a several hour observation, Doppler Setting will have corrected for the almost constant Heliocentric velocity (~ 30 km/s), but cannot exactly correct the variation of ~ 0.5 km/s for the Earth's rotation.
- Remaining corrections done in e.g. tasks `mstransform`, `cvel` and `tclean` in CASA. CASA task `plotms` can correct on-the-fly (less accurately).

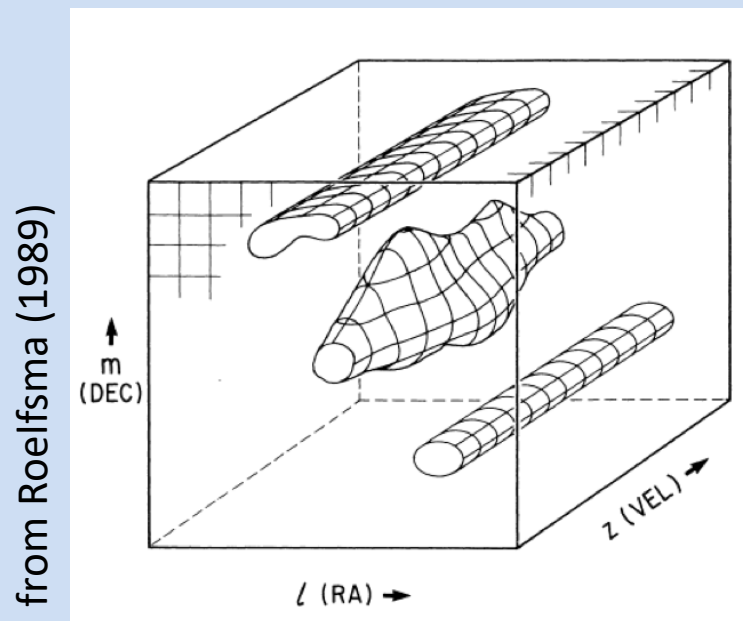
Different colours
are different
times in the
observation



Continuum subtraction

As well as lines, spectral-line data often contain continuum sources (either from the target or from nearby sources in the field of view)

- This emission complicates the detection and analysis of line data
- Continuum emission limits the achievable spectral dynamic range

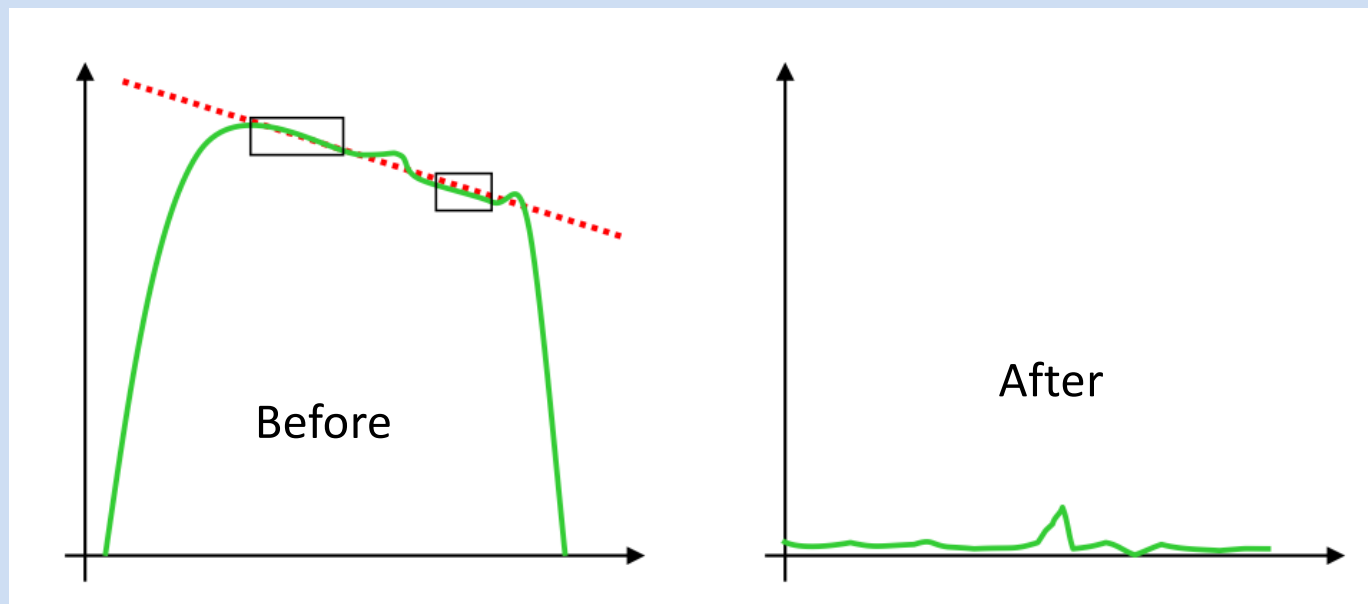


Spectral line cube with two continuum sources (structure independent of frequency) and one spectral line source near the field centre

Continuum subtraction

Method:

- 1) examine the data
- 2) assess which channels appear to be line-free
- 3) use line-free channels to estimate the continuum level
- 4) subtract the continuum
- 5) evaluate the results



Continuum subtraction

Two methods:

1. In the uv-plane

Subtract continuum → image/clean line & continuum separately

Use CASA tasks such as mstransform and uvcontsub

2. In the image-plane

Image/clean data → subtract continuum from image cube (CASA imcontsub)

OR

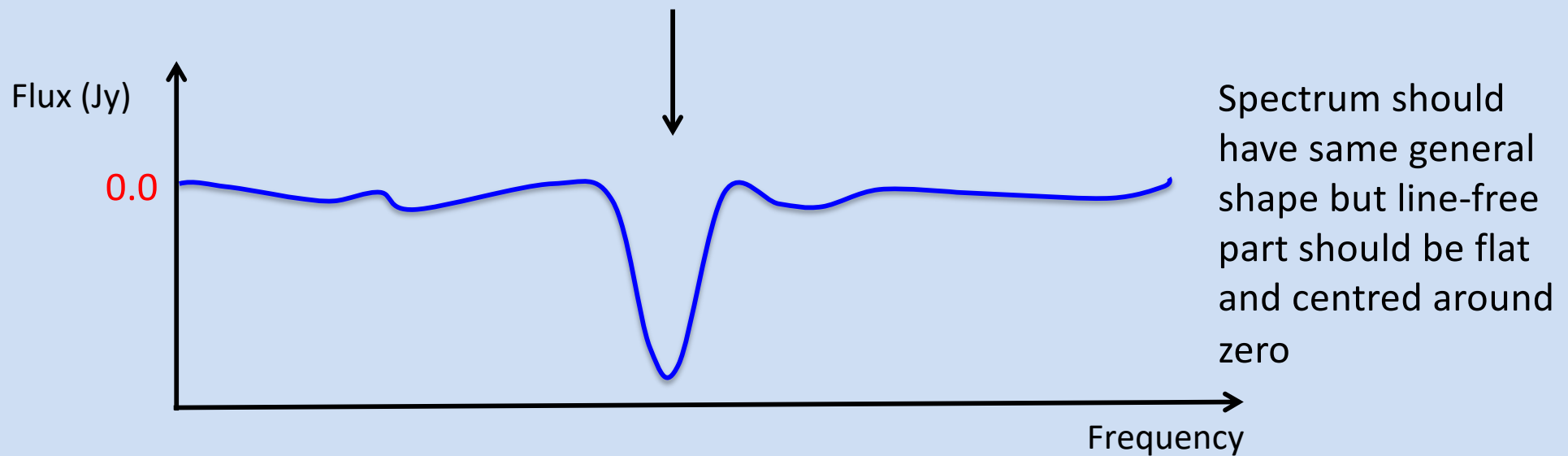
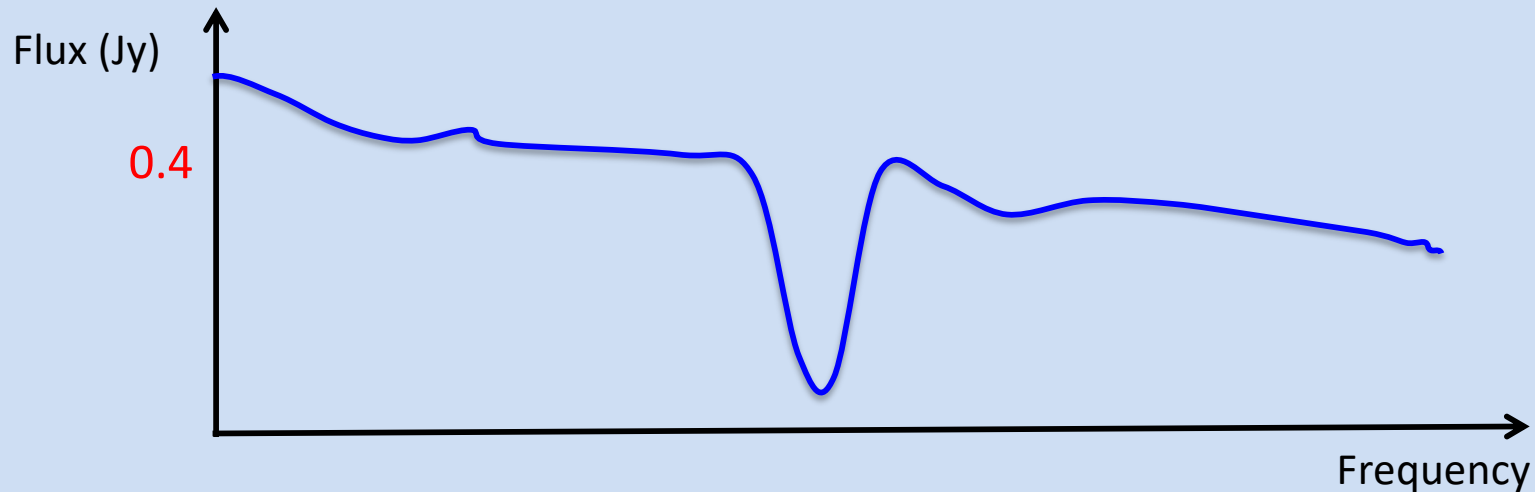
FT data → subtract continuum from 'dirty' cube

→ clean continuum & line separately (e.g. AIPS IMLIN)

No one single subtraction method is appropriate for all experiments!

Continuum subtraction

Did it work?



Imaging of cubes

- Principles for continuum imaging mostly applies to line data as well (cleaning, weighting, etc.)
- But keep in mind that deconvolution of spectral line data often poses special challenges:
 - Cleaning many channels is **computationally expensive** (do you need the full spectral resolution or can average?)
 - Emission ***structure* changes from channel to channel** (may have to change cleaning boxes for each channel)
 - If you are interested in *both* high sensitivity (to detect faint emission) and high spatial/spectral resolution (to study kinematics):
robust weighting with $-1 < R < 1$ good compromise

Part III: Image and Spectral Analysis

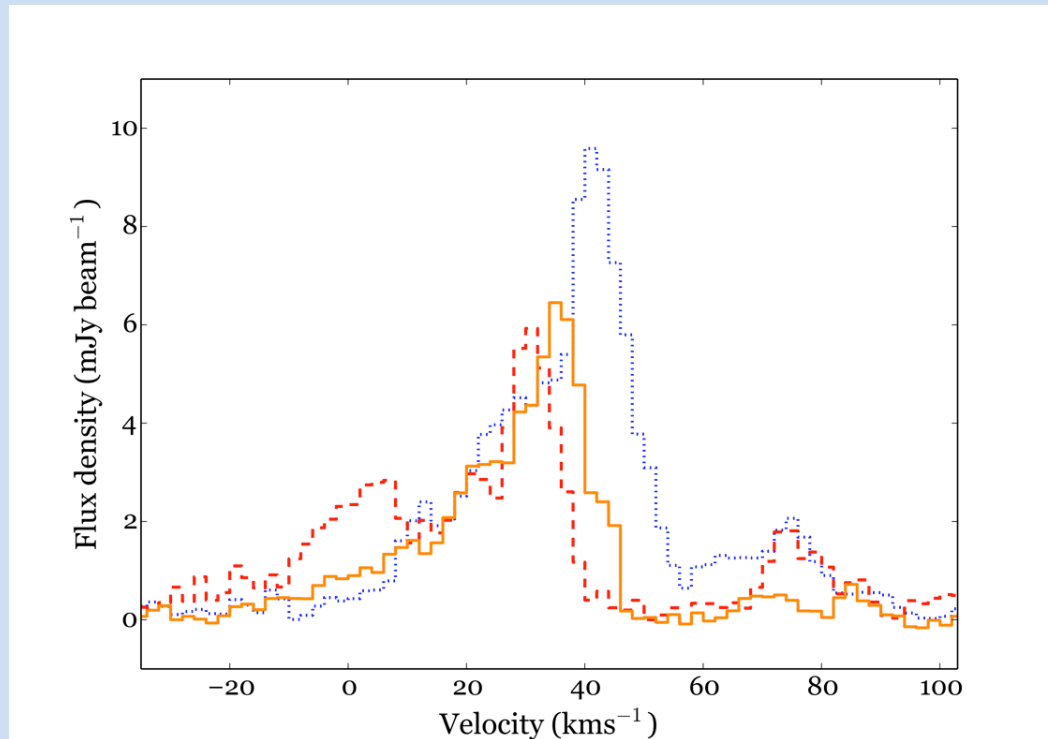
After mapping all channels in the data set, we have a **spectral line 3D data cube** (RA, Dec, Velocity or Frequency)

To visualize the information we usually make 1-D or 2-D projections providing different analysis methods:

- Line profiles (1-D slices along velocity axis)
- Channel maps (2-D slices along velocity axis)
- Moment maps (integration along the vel. axis)
- Position-velocity plots (slices along spatial dimension)

See advanced spectral line (ALMA) tutorial on Thursday!

Line profiles



Johnston et al. (2014)

Spectra taken at different positions in a cube of ^{13}CO (J=2-1) emission.

The cube was created by combining SMA and IRAM 30-m data.

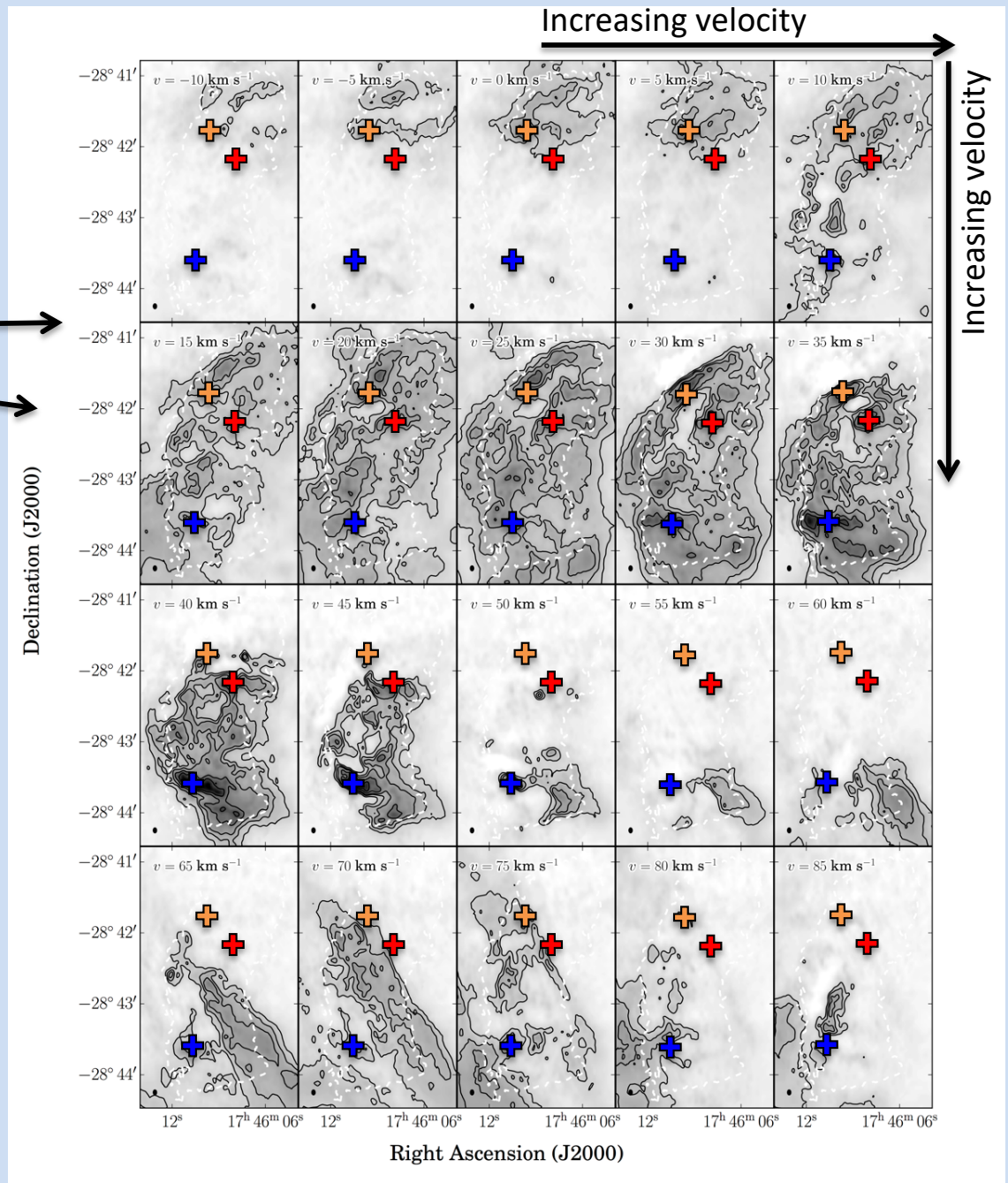
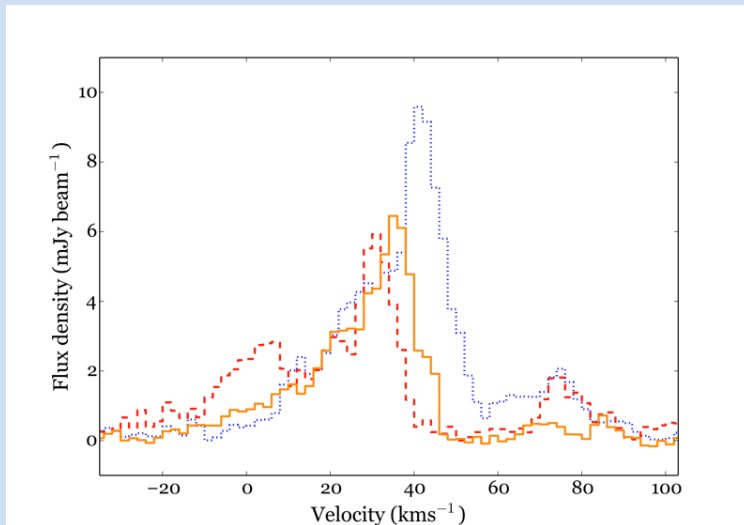
Use the Spectral Profile tool in the CASA viewer

Channel maps

Channel maps of ^{13}CO ($J=2-1$) emission from a Cloud near the Galactic Centre

Channels are from -10 to 85 km/s (in steps of 5 km/s)

Coloured \oplus show the positions where the spectra on the previous slide were measured



Johnston et al. (2014)

Moment maps

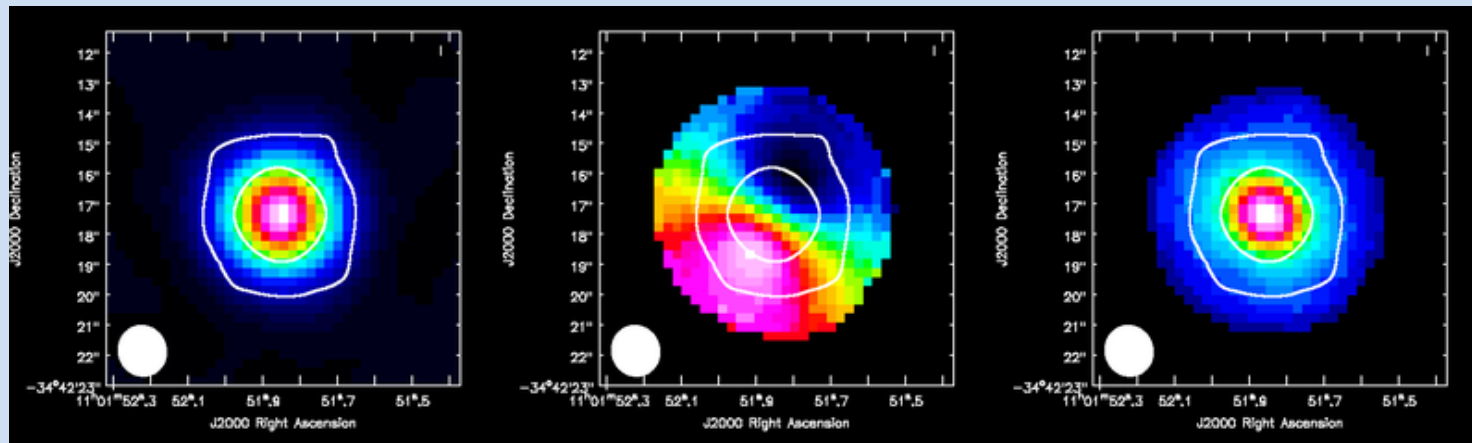
Use moment maps to derive parameters such as integrated line intensity, centroid velocity and line widths as function of position:

$$I_{\text{tot}}(\alpha, \delta) = \Delta v \sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i) \quad \leftarrow \text{Total intensity (Moment 0)}$$
$$\bar{v}(\alpha, \delta) = \frac{\sum_{i=1}^{N_{\text{chan}}} v_i S_{\nu}(\alpha, \delta, \nu_i)}{\sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i)} \quad \leftarrow \text{Intensity-weighted velocity (Moment 1)}$$
$$\sigma_v(\alpha, \delta) \equiv \sqrt{\langle (v_i - \bar{v}(\alpha, \delta))^2 \rangle} \quad \leftarrow \text{Intensity-weighted velocity dispersion (Moment 2)}$$
$$= \sqrt{\frac{\sum_{i=1}^{N_{\text{chan}}} (v_i - \bar{v}(\alpha, \delta))^2 S_{\nu}(\alpha, \delta, \nu_i)}{\sum_{i=1}^{N_{\text{chan}}} S_{\nu}(\alpha, \delta, \nu_i)}}$$

Can be made with CASA task immoments

Moment maps

HCO⁺(4-3) moment maps of TW Hya with ALMA (white is continuum)



Zero Moment
Integrated flux

Moment 1
Mean velocity

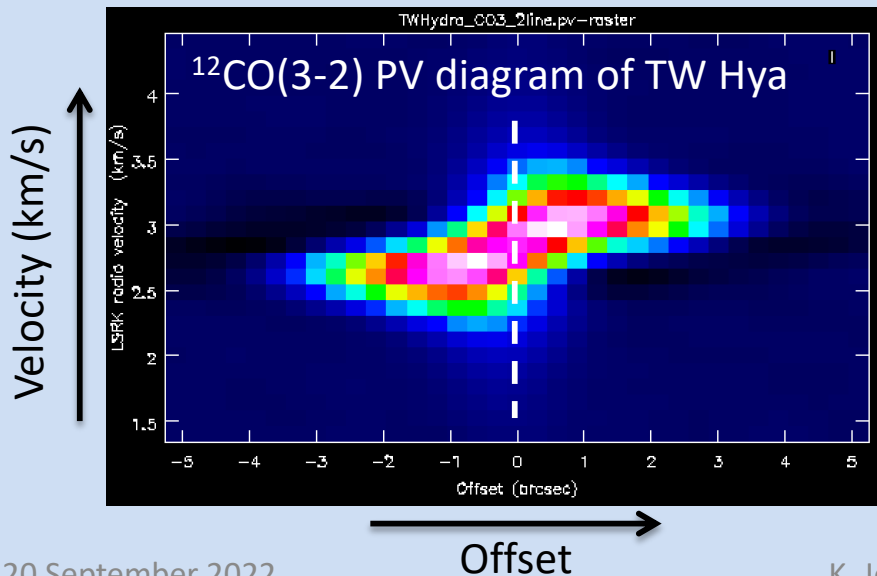
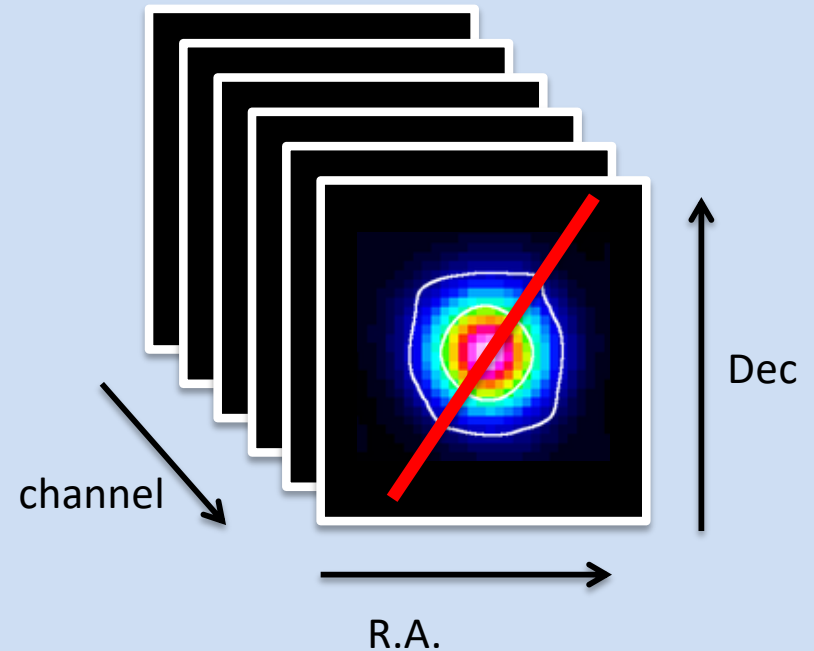
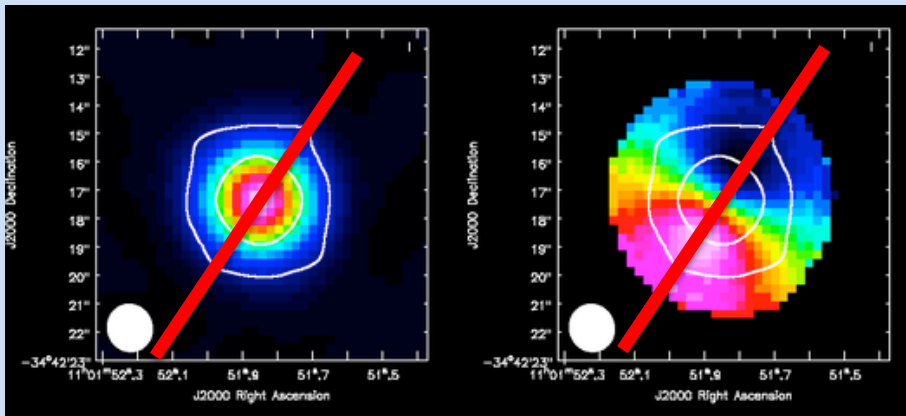
Moment 2
Velocity Dispersion

Moments are sensitive to noise so clipping is required:

- Sum only over the planes of the data cube that contain emission
- Since higher order moments depend on lower ones (so progressively noisier), set a conservative intensity threshold for 1st and 2nd moments

Position-Velocity (PV) diagrams

PV diagrams take a slice out of a cube along a “PV cut” (e.g. red line shown below)



You can produce PV diagrams directly in CASA using task `impv`, or using the task `immoments`, by collapsing the RA or DEC axis



Summary



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Having a third axis (frequency or velocity) provides you with a lot of extra information about the physics of your observed source.

To recap, we covered:

- Setting up your observation
- Data reduction
- Image and spectral analysis

You're now ready to do some spectral line proposing, observing and reduction!